

SHORT CIRCUIT CURRENT ENHANCEMENT IN GaAs/Al_xGa_{1-x}As MQW SOLAR CELLS

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ABSTRACT: The GaAs/Al_xGa_{1-x}As quantum well solar cell (QWSC) shows promise as a novel approach to higher efficiency solar cells but suffers from a poor short circuit current J_{sc} . We report on efforts to reduce this problem with the use of compositional grading and back surface mirroring. We present experimental quantum efficiency (QE) data on a range of compositionally graded QWSCs and devices in which the back surface of the cell is coated with a mirror, increasing the optical thickness of the quantum well layer in the long wavelength range. The experimental QE spectra are reproduced by a model which deals with arbitrary compositional profiles and optical cavities formed in the mirrored cells. The model is used to design an optimised QWSC, and projected J_{sc} values given. Applications including II-VI and tandem solar cells are considered.

Key words: Quantum Well - 1: AlGaAs/GaAs - 2: Tandem - 3

1 INTRODUCTION

The Quantum Well Solar Cell (QWSC) was first proposed by Barnham and Duggan [1] to enhance efficiency by absorption of below bandgap radiation in the wells. This design shows an open circuit voltage (V_{oc}) greater than those expected of cells made from material with the quantum well effective bandgap [2]. The QWSC is therefore promising as an efficient solar cell design.

The GaAs/Al_xGa_{1-x}As system [3] is an attractive material for the design of a QWSC since GaAs quantum wells in Al_xGa_{1-x}As are unstrained, and have been extensively studied for a wide range of optoelectronic devices. Previous work [4] has demonstrated a GaAs/Al_xGa_{1-x}As QWSC with an efficiency of 14.5% AM1.5 and a higher V_{oc} than that of the highest efficiency GaAs device [3]. The overall efficiency remains low because of a low short circuit current density (J_{sc}). This is due to inefficient minority carrier transport in Al_xGa_{1-x}As and the limit on the number of wells which can be incorporated.

This work applies compositional grading techniques to address the transport issue, and light trapping to increase the quantum well absorptivity.

2 INCREASING J_{sc}

Figure 1 shows a schematic of a graded, mirror backed QWSC. The back surface mirror causes light to perform several passes through the cell. This technique is well suited to the QWSC design since the wells convert light to current with nearly 100% efficiency, but have a relatively low absorptivity.

The compositionally graded p type emitter layer has a bandgap which increases towards the surface. Minority carriers generated in this region experience a pseudo-electric field due to the bandgap gradient and diffuse preferentially towards the junction. This increases minority carrier collection efficiency ([5] - [10]). This technique also reduces the overall absorptivity of the emitter layer and boosts the generation rate in the efficient intrinsic i layer.

The pseudo-electric field gradient increases QE at short wavelengths, and the reduced emitter absorptivity increases QE close to the bandgap E_g .

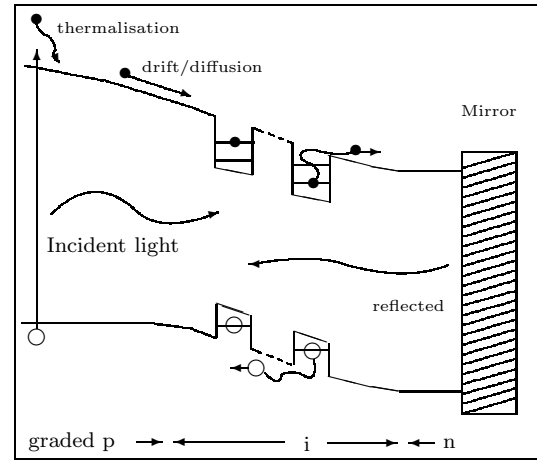


Fig. 1. Schematic of a graded and mirror backed showing generation, thermalisation and drift in the graded p layer

3 LIGHT INTENSITY IN A QWSC

The light intensity in a QWSC with a back mirror (figure 1) is determined by calculating the electric field strength in the solar cell as a function of position and wavelength, for position dependent optical parameters [12]. The parameters used are defined in Table 1. The total normalised light amplitude \mathcal{E} inside the cell is found by summing successive reflections from front and back surfaces to infinity, and can be expressed as:

$$\mathcal{E} = \left(\frac{e^{-\int_0^x k dx'} + \frac{r_b e^{-2\int_0^d k dx'}}{e^{-\int_0^x k dx'}}}{1 - r_f r_b e^{-2\int_0^d k dx'}} \right) \quad (1)$$

The light intensity in the solar cell is then given by

$$\mathcal{I}(x, \lambda) = \mathcal{I}_i (1 - R) (\mathcal{E} \mathcal{E}^*) \quad (2)$$

and hence the generation rate at any position is

$$G(x, \lambda) = \alpha(x, \lambda) \mathcal{I}(x, \lambda) \quad (3)$$

Parameter	Meaning
λ	wavelength
α	absorption coefficient [13],[4]
n	refractive index [13]
k	complex wavevector $= \frac{\alpha}{2} - \frac{2\pi i n}{\lambda}$
R	measured reflectivity
r_f	front surface complex amplitude reflectivity
r_b	back surface complex amplitude reflectivity

Table 1
Parameters needed by the light intensity calculation

4 PHOTOCURRENT AND QE MODEL

The photocurrent in the charge neutral sections of the emitter and base layers is calculated by solving minority carrier current and continuity equations with position dependent parameters [12]. The equation takes the following form

$$\frac{d^2 n}{dx^2} + b(x) \frac{dn}{dx} + c(x)n + g = 0 \quad (4)$$

where n is the minority carrier concentration and the parameters are defined in Table 2. This equation is solved numerically using standard second order numerical methods. The boundary conditions are $n = 0$ at the depletion edge in the low injection depletion approximation, and a surface recombination current given by the surface recombination velocity [11]. The photocurrent from the p and n layers is then given by the gradient of the minority carrier concentration at the $p-i$ and $i-n$ interfaces respectively. In the depletion approximation, all carriers generated in the i layer are collected. The current from the i layer is then simply the integral of the generation rate across it.

The photocurrent density J_{ph} is given by the sum of p, i and n layer photocurrent contributions. The QE of the cell is then

$$QE(\lambda) = \frac{j_{ph}(\lambda)}{qI_i(\lambda)} \quad (5)$$

5 EXPERIMENTAL RESULTS

5.1 Samples

Sample were grown by MBE at Imperial College and by MOVPE at the University of Sheffield III-V Facility. 30 and 50 well QWSCs with and without compositional grades were grown. Control samples are identical in structure to the QWSCs except that the well material is replaced with $\text{Al}_x\text{Ga}_{1-x}\text{As}$ with the same composition as the barrier. The wafers were processed into test devices at Sheffield. These are circular 1mm diameter mesa structures with a 0.545mm diameter optical window.

Samples with back surface mirrors were processed by etching the GaAs substrate down to the back of the QWSC structure under the optical window. The back surface of the n region acts as an etch stop. The resulting pit is then coated with a metallic mirror.

Parameter	Meaning
X	aluminium mole fraction
D	diffusivity [10]
L	diffusion length [10],[14],[15]
E	effective electric field [5],[6],[8] $= \nabla_x E_g$
S	surface recombination velocity [9]
\mathcal{E}_f	normalised effective field $= qE/(k_B T)$
\mathcal{D}_X	normalised diffusivity field $= \nabla_X D/D$
b	field-like parameter $= \mathcal{E}_f + \mathcal{D}_X$
c	diffusion length-like parameter $= \mathcal{E}_f \mathcal{D}_X + \nabla_x \mathcal{E}_f - L^{-2}$
g	normalised generation rate $= G/D$

Table 2
Definitions of model parameters with references

5.2 Modelling

The model is used to reproduce experimental data. The model parameters listed in Table 2 are determined by growth. The QE of samples without compositional grades is sensitive to the diffusion length L at wavelengths near the emitter band edge, and to S , the ratio of surface recombination velocity and diffusivity, at short wavelengths. Therefore, we use L and S as independent fitting parameters.

Modelling shows that graded samples are relatively insensitive to diffusion length. They are highly sensitive, however, to the parameter \mathcal{D}_X defined in table 2, which reflects how rapidly the diffusivity D varies with Al fraction. In the absence of direct measurements of D as a function of composition, we assume an exponential dependence [12] of D on X , as recommended by Hamaker [10], which reduces \mathcal{D}_X to a constant. The values needed to reproduce the data are similar or better than those reported by Hamaker.

Comparison with published values gives us an indication of the efficiency of minority carrier transport in our material. We find that our values are lower than published numbers at aluminium fractions above about 0.3, indicating worse minority carrier transport.

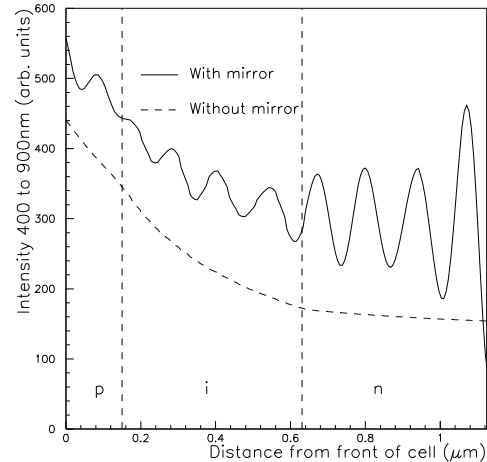


Fig. 2. Total light intensity 400-900nm in a QWSC with and without a mirror

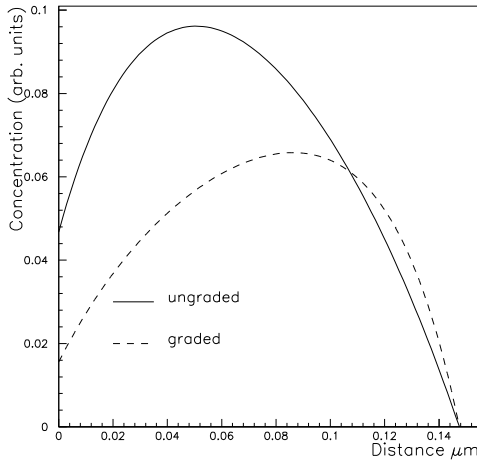


Fig. 3. Minority carrier concentration in a p type emitter with and without a compositional grade

5.3 Results

Figure 2 shows the panchromatic increase in light levels in a QWSC structure with and without a mirror. Fabry-Perot oscillations are visible in the mirrored case. Figure 3 shows minority carrier profiles in a 0.3 Al fraction p type emitter and in an identical emitter with an Al fraction graded from 0.4 to 0.3. We note that the gradient of the minority carrier concentration is decreased at the surface and increased at the p - i interface. The former implies a reduced surface recombination, and the latter an enhanced J_{sc} .

Figure 4 shows the experimental QE of the an ungraded 30 well QWSC with and without a back surface mirror. Also shown is the model for this cell, showing good agreement. The experimental short circuit current enhancement under an AM1.5 spectrum is 27% in this case.

Figure 5 shows experiment and modelling for a 30 well QWSC with a base aluminium fraction of 0.30 graded to 0.67 over $0.15\ \mu\text{m}$, also showing a good fit. The J_{sc} enhancement due to the grade is 24%.

This gives an combined overall J_{sc} increase of over 50% extra J_{sc} for a 30 well QWSC with both design improvements. The percentage enhancement due to the mirror decreases as more wells are introduced and the mirror becomes redundant. Similarly, the enhancement due to the grade decreases as the material quality is improved, and the grade also becomes unnecessary.

6 Optimised QWSCs

6.1 Present Material

Having separately established the viability of both techniques for enhancing the J_{sc} , we use the model to predict an optimised design. The p layer is thinned to $0.1\ \mu\text{m}$ in order to reduce losses in the p layer without compromising the series resistance characteristics. The base aluminium fraction is set at 0.30, for which an optimum of 0.40 at the top of the grade is found. Transport parameters are consistent with those observed in present material.

Experience shows that 50 wells can safely be incorporated into the i region without compromising the voltage performance of the QWSC. Modelling of this cell is shown in figure 6, and produces a short circuit current increase of 39% compared to a suitable 50 well QWSC control with a standard $0.15\ \mu\text{m}$ p

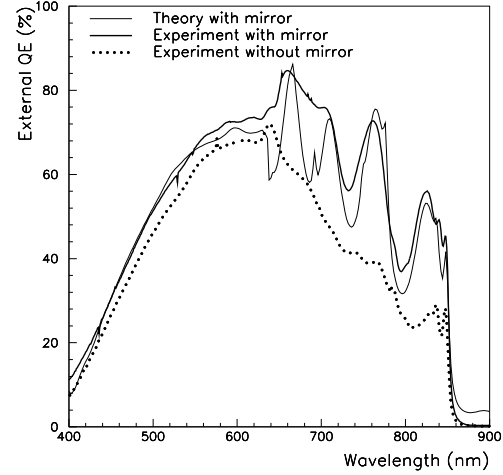


Fig. 4. QE of a 30 well QWSC with and without mirror, together with theory for the mirrored case

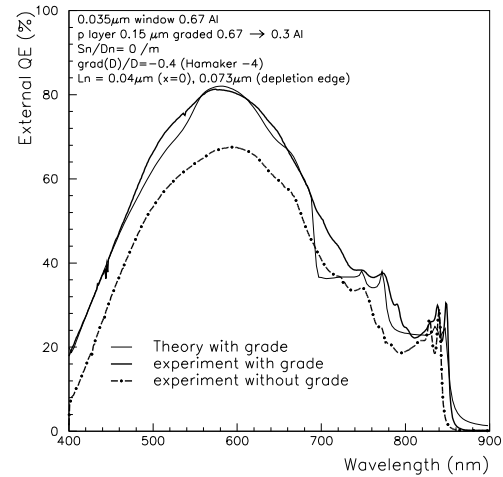


Fig. 5. Experimental data and theoretical fit for a 30 well QWSC with a base aluminium fraction of 0.30 graded to 0.67 over $0.15\ \mu\text{m}$

layer, no grade, and no mirror. The efficiency prediction for the optimised structure is between 19% and 20%, using the dark current of a 50 well QWSC.

6.2 Ideal Material

Further efficiency enhancements are possible in material with improved minority transport parameters. Ludowise [16] reports very high diffusion lengths in a series of solar cell samples grown by MOVPE. These values were derived from internal QE spectra, using a method similar to the one used by us.

An optimisation based on the Ludowise diffusion length of $L_n \sim 1.4\ \mu\text{m}$ at Al fraction 0.30 yields a value of $J_{sc} = 25.6\ \text{mAcm}^{-2}$. This corresponds to an efficiency between 21% and 24% for low and high values of FF and V_{oc} in AM1.5. These results apply to a 50 well sample with a back surface mirror, a $0.02\ \mu\text{m}$ window of composition 0.9 Al, no compositional grade and an optimum p layer thickness of $0.15\ \mu\text{m}$.

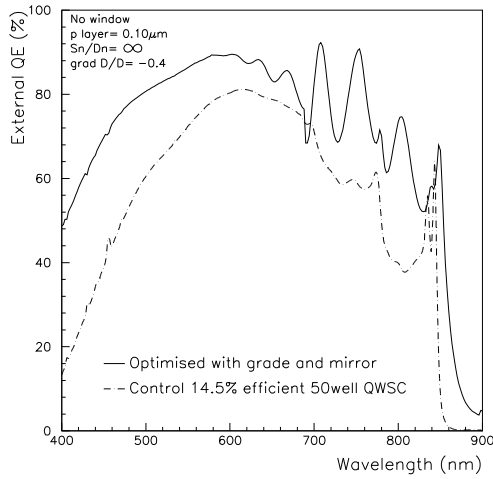


Fig. 6. Comparison of experimental QE for 14.5% AM1.5 efficient QWSC and theoretical projection for the optimised device with grade over $0.01 \mu\text{m}$ and back surface mirror

7 Further Applications

Similar techniques may be applied to other materials which suffer from minority carrier transport problems such as CdHgTe or CuInGaSe.

The short circuit current of a QWSC may be easily tailored by changing the number and/or width of the quantum wells, without affecting the p and n layers. This means that the design of the conventional part of the cell need not be compromised by current matching requirements. We therefore propose another application which is the tandem QWSC. Ideally, this would use two QWSCs, but here we present a preliminary example in GaAs/Al_xGa_{1-x}As.

The QE of a structure optimised for AM1.5 is shown in figure 7. The top cell is based on previous high Al fraction samples. It has a $0.075 \mu\text{m}$ p type emitter graded from 0.67 to 0.48 Al and an $0.8 \mu\text{m}$ i layer. The bottom cell is a standard high efficiency GaAs design. The QE and J_{sc} values compare favourably with the tandem world record holder, a cell reported by Takamoto [17]. Furthermore, we expect higher voltages [2]. Excluding shading, we find that 41 wells of width 31\AA are sufficient to match currents at 13.6mA cm^{-2} . Under AM0, currents are matched simply by reducing the number of wells to 33 for a J_{sc} of 16.0mA cm^{-2} .

8 Conclusion

Both compositional grading and back surface mirror techniques can significantly increase the J_{sc} of an Al_xGa_{1-x}As QWSC, and is particularly suited to poor material. In general, J_{sc} optima are found at smaller grades as the emitter efficiency improves. Theory shows that mirrors help QWSCs made from efficient material, but that grades are unnecessary in this case. We predict efficiencies of up to 20% with existing material, or 24% with optimum material.

We conclude that the compositional grading technique is of interest for QWSCs, and solar cells in general which are made from material with low minority carrier transport efficiency. They may furthermore be attractive for tandem applications both because of potentially higher voltages, and because of the simplified current matching properties.

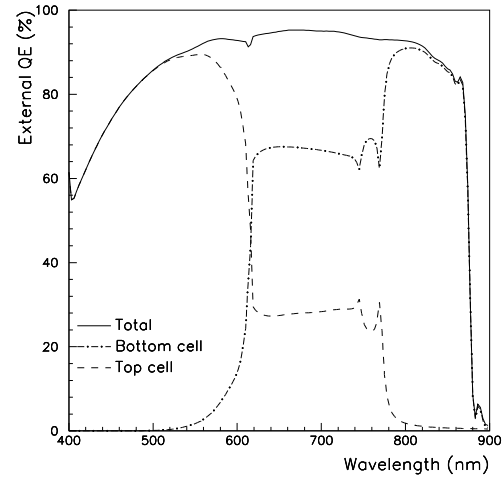


Fig. 7. Illustrative example of a QWSC tandem

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